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Research article

Multi-hazard risk assessment of coastal vulnerability from tropical cyclones – A GIS based approach for the Odisha coast

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A B S T R A C T

The coastal region bordering the East coast of India is a thickly populated belt exposed to high risk and vulnerability from natural hazards such as tropical cyclones. Tropical cyclone frequencies that develop over the Bay of Bengal (average of 5–6 per year) region are much higher as compared to the Arabian Sea thereby posing a high risk factor associated with storm surge, inland inundation, wind gust, intense rainfall, etc. The Odisha State in the East coast of India experiences the highest number of cyclone strikes as compared to West Bengal, Andhra Pradesh, and Tamil Nadu. To express the destructive potential resulting from tropical cyclones the Power Dissipation Index (PDI) is a widely used metric globally. A recent study indicates that PDI for cyclones in the present decade have increased about six times as compared to the past. Hence there is a need to precisely ascertain the coastal vulnerability and risk factors associated with high intense cyclones expected in a changing climate. As such there are no comprehensive studies attempted so far on the determination of Coastal Vulnerability Index (CVI) for Odisha coast that is highly prone to cyclone strikes. With this motivation, the present study makes an attempt to investigate the physical, environmental, social, and economic impacts on coastal vulnerability associated with tropical cyclones for the Odisha coast. The study also investigates the futuristic projection of coastal vulnerability over this region expected in a changing climate scenario. Eight fair weather parameters along with storm surge height and onshore inundation were used to estimate the Physical Vulnerability Index (PVI). Thereafter, the PVI along with social, economic, and environmental vulnerability was used to determine the overall CVI using the GIS based approach. The authors believe that the comprehensive nature of this study is expected to benefit coastal zone management authorities.

1. Introduction

There are numerous environmental issues that link the components of the earth system atmosphere-ocean-land interactions as a big challenge in the sustainable development of the coastal zone. Some of the factors that contribute to these environmental issues include sea level rise, saltwater intrusion, climate change, oil spills, tropical cyclones, solid waste pollution, anthropogenic induced disasters, etc. In a global perspective, nearly two-third of the human population have their habitat within 400 km of a coast, and more than half of this population depends on the coastal strip of 200 km for their livelihood. As per the 2011 Census by the Government of India, about 14.2% of human population resides in the coastal districts and the population density trend is increasing at present. However, the degree of physical and social vulnerability on the population density along the coastal belts associated with natural hazards such as tropical cyclones can vary and have wider consequences.

Recent research indicates that tropical cyclones that form over the Bay of Bengal have intensified in terms of cyclone size and maximum sustained wind speed during the past few decades (Murty et al., 2016). A recent study for the Bay of Bengal basin by Sahoo and Bhaskaran (2016) clearly indicate a drastic increase in the Power Dissipation Index (PDI), a widely used metric (Emanuel, 2005) that represents the destructive potential of tropical cyclones. It could be attributed due to global warming resulting in rising ocean temperatures and other climatic perturbations; however a much detailed study is warranted to ascertain this fact. The East coast of India has experienced about 200 cyclonic storms (Sahoo and Bhaskaran, 2015, 2016) in the past 42 years (1970–2012) that resulted in a huge loss of life and property. For example, the 2009

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Aila cyclone has breached and destroyed the 400 km long stretch of embankment as extreme waves entered the flood plains in West Bengal resulting in a major catastrophe. The intrusion of seawater during this event affected almost 2 million people marooned for several days that affected agriculture as well the drinking water supply. The intrusion of saltwater resulted in farm lands turning out non-productive. There was another extensive calamity that resulted from the 1999 Odisha Super cyclone and the 2013 *Phailin* cyclone that made landfall in the Odisha coast. A real-time storm surge warning system and information dissemination in place developed by the Indian National Centre for Ocean Information Services (INCOIS) under the Ministry of Earth Sciences, Government of India have provided timely warnings and alerts to the National Disaster Management Authority (NDMA) that resulted in one of the massive evacuation efforts saving human lives during the Phailin event (Murty et al., 2014) as compared to the 1999 Odisha Super cyclone event. Hence there is a need to develop a comprehensive coastal vulnerability index map by considering the combined effects of physical, environmental, social, and economic aspects for an effective coastal zone management plan and evacuation planning operations prior to the landfall of a cyclone having wider socio-economic implications.

Vulnerability refers to the exposure of risk with respect to susceptibility and resilience (Balica and Wright, 2009; Scheuer et al., 2011). It can be indexed for consistent characterization of relative risk associated with given parameters for a given set of locations. In this context, the Coastal Vulnerability Index (CVI) is the most commonly used metric to evaluate the risk associated along the coastal region due to multiple impacts from physical, environmental, social, and economic drivers during post-hazard event. There are numerous studies conducted worldwide to determine various aspects of relative coastal vulnerability and the risk factors using several proven techniques. For example, the study by Doukakis (2005), Balica et al. (2012), Addo (2013) are some of the pioneering studies on coastal vulnerability due to sea level rise and coastal flooding. For the Indian coast, a comprehensive study by Sudha Rani et al. (2015) provides a detailed review on the overall assessment and methodology of CVI. Other studies for the Indian coast pertaining to CVI due to sea level rise for the entire Tamil Nadu coast using four variables was reported by Kumanan et al. (2010); due to extreme waves for Kalpakkam coast using seven variables reported by Nayak and Bhaskaran (2014), due to tsunami wave run-up height using seven fair weather parameters for Odisha region was reported by Kumar et al. (2010). Bahinipati (2014) reported on the district wise sensitivity study of physical, social, economic, and environmental vulnerability for the Odisha State.

In a global perspective based on resilience factor the studies by Wu et al. (2002), Boruff et al. (2005), Bjarnadottir et al. (2011), Logan and Xu (2015) have reported on the social, economic and environmental vulnerability along with the physical vulnerability. As mentioned above there are many approaches used by several researchers, and the one using Principal Component Analysis (PCA) as an efficient method to quantify vulnerability was reported by Cutter et al. (2003). Armaş and Gavriş (2013); Borden et al. (2007); Fekete (2009); Schmidtlein et al. (2008); Tate (2012) are some of the notable works that used PCA for the computation of social vulnerability. The analytical hierarchy method was used by Mani Murali et al. (2013) and GIS based method was reported by Fernandez et al. (2016), Beluru Jana and Hegde (2016) to assess vulnerability from various factors.

The present study provides an in depth evaluation on the coastal vulnerability for the Odisha coast associated with landfalling tropical cyclones. In comparison to prior studies conducted over this region, the novelty of this work is the inclusion of an additional parameter on coastal inundation that is considered extremely important associated with storm surge events. In addition the study estimates the CVI from the combined effects due to storm surge and onshore inundation in terms of inundation volume that provides a concise notion to assess the risk and damage due to seawater intrusion inland during tropical cyclone activity. Das and Vincent (2009) showed that mangroves played an important role in protecting villages and reduced the death toll during the 1999 Odisha Super cyclone. Their study (Das and Vincent, 2009) show that villages with wider mangrove belts experienced lesser impact from storm surge compared to those regions with no mangroves. The present work does not account for storm surge interaction with mangroves, as the spatial distribution of mangroves for the Odisha State is very limited. Another study by Kumar et al. (2010) and Bahinipati (2014) have not considered the impact of coastal inundation characteristics in the overall vulnerability assessment. Also other than using the conventional formulation and methods to estimate CVI, the approach in the present study uses the synaptic ARCGIS toolbox to estimate CVI along the Odisha coast. The determination of physical CVI uses ten ocean and atmospheric drivers including the case for high intense cyclones expected in a changing climate scenario. Thereafter, the estimated physical CVI is combined with social, economic, and environmental vulnerability to provide an integrated overview on the combined CVI for the Odisha coast using the demographic and survey records of India. The subsequent sections deal with the data and methodology, followed by the results and discussion, and finally the summary and conclusions of the study.

2. Data and methodology

The study used datasets from various sources to estimate the combined effect of physical, environmental, social, and economic impacts in the overall determination of CVI for coastal Odisha. The sub-sections below provide detailed information on the various datasets and methodology used grouped into (i) combined effect due to storm surge and inundation along the coast (highlighting on the inundation volume), (ii) Physical Coastal Vulnerability Index (PVI) using 10 parameters, (iii) Social and Economic Vulnerability (referred as SVI in the text), (iv) Environmental Vulnerability Index (referred as EVI in the text), (v) Integrated Coastal Vulnerability Index (CVI) that constitutes the combined impact of PVI, SVI, and EVI. The IPCC (2007) report states that coastal communities around the world would experience higher coastal flooding due to climate change effects. A recent study by the authors also points out there would be a 7% increment in the intensity of tropical cyclones based on the futuristic trend estimate of Power Dissipation Index (PDI) for the Odisha coast. Keeping this in view, the present study also performed calculations of storm surge and coastal inundation for tropical cyclones considering an upper bound of 11% higher intensity expected in a changing climate scenario (Knutson et al., 2010). The upper bound of 11% used in this study may be justified for the worst possible scenario. The Coupled Model Intercomparison Project (CMIP5) and IPCC (Intergovernmental Panel on Climate Change) have generated different scenarios of wind speed estimates from climate models based on varying Representative Concentration Pathways (RCPs) for the entire globe. The RCPs are the concentration trajectories from four greenhouse gases that was adopted by IPCC in the Fifth Assessment Report (AR5) published in 2014 (IPCC, 2014). The scenarios are generated from four pathways viz; RCP8.5, RCP6, RCP4.5, and RCP2.6. However, the data generated from the climate models needs appropriate downscaling for the region of interest, and also the data quality needs to be thoroughly verified with in situ and available observations. A comprehensive validated dataset of wind speed and its variability in a changing climate from climate models are not available for the

region of interest (Odisha coast), and therefore the present study use the empirical way to account for the impact of climate change.

2.1. Combined effects of storm surge and inundation

From literature review it is evident that no prior studies were conducted for the Indian coast that takes into account the combined effect due to storm surge and inundation herein represented as 'inundation volume' during the landfall of a tropical cyclone. Representing the coastal vulnerability and risk assessment in terms of inundation volume is quite important and pertinent for planning operations. A study by Ali (1999) reports that in a global perspective, India accounts for nearly 23% loss of life during tropical cyclones, and about 90% of the overall loss accounts from inland flooding and storm surge near the coast (Dube et al., 1997). Table 1 show that the relationship between storm tide near the coast and the extent of onshore inundation is not a linear function. As seen from this table, the coastal locations along the southern and central portion of Odisha from Baruva to Konark display the relationship between storm tide and inundation extent quite different as compared to the northern portion (from Jagatsinghpur to Chandipur) mainly attributed due to variations in the onshore topography. The variation as seen from this table brings to light the importance of inundation volume. Therefore, considering the combined effects of storm surge and inundation as inundation volume is very much relevant in this context. A detailed description on the datasets used to estimate storm surge and onshore inundation is provided in the subsequent section. The inundation volume is a representation for the net amount of seawater pushed onshore due to the impact of cyclone wind stress. As an example, for land elevation with uniform onshore topography, the volume of seawater penetrated inland can be estimated as $0.5 \times$ (Surge height) $\times$ (Inundation Extent) $\times\ n$ (where, n is the alongshore distance).

2.2. Physical coastal vulnerability parameters

The physical aspects of coastal vulnerability attributes due to variety of environmental drivers such as storm surge, extent of onshore inundation, tidal range, rainfall, slope of continental shelf, topographic slope, rate of shoreline changes, coastal geomorphology, mean wave height, and relative sea level change. Table 2 provides an overview on physical parameters and the source of data used for the present study to compute the relative PVI. In a previous study, the authors have generated a comprehensive dataset on storm surge and associated inundation (Sahoo and Bhaskaran, 2017) for the entire 480 km coastline of Odisha state using multiple synthetic cyclone tracks (Sahoo and Bhaskaran, 2016). The synthetic track referred here denotes the most probable cyclone track that was constructed based on historical cyclone tracks available from the records of India Meteorological Department (IMD). Sahoo and Bhaskaran (2017) performed several numerical experiments with the synthetic track for different combination of cyclone parameters such as varying intensity, varying track angle with respect to landfall location, and varying translation speeds. These numerical experiments led to the development of a comprehensive dataset of storm surge and inundation scenarios for the entire 480 km coastal stretch of Odisha state. Their study used 11 synthetic tracks spatially separated by a distance of 40 km each covering the entire coastline of Odisha. Thereafter, the Advanced Circulation Model (ADCIRC) using the synthetic track information computed the storm surge characteristics and associated onshore inundation. The ADCIRC simulation used five different wind intensities such as 110, 120, 130, 140, and 150 knots. The ADCIRC simulation that used wind intensity of 150 knots represents the scenario corresponding to 10% increase expected in a changing climate (futuristic projection). The experiments were carried out using a constant translation speed of 6 km/h. The ADCIRC study domain encompasses an area of nearly 800 km cross-shore (along offshore direction), 480 km along-shore (covering the coastline of Odisha state), and +10 m topo-line along the landward boundary to calculate the inundation during storm surges. The study used a fine mesh for the nearshore regions (~200 m) that relaxes to about 20 km along the offshore boundary. The cold start mode was used for model execution and integrated for 60 days to attain the steady state condition. The Le Provost et al. (1995) tidal constituents were specified along the offshore boundary nodes. The cyclonic wind field was generated using the Holland (1980) parametric wind formulation. Overall the study (Sahoo and Bhaskaran, 2017) performed a total of 220 numerical experiments with 44 synthetic tracks to generate multiple scenarios of storm surge and inundation maps. From this dataset, the optimum (maximum) storm surge and inundation maps were extracted to compute the physical coastal vulnerability for the Odisha coast.

The tidal range was obtained from the depth integrated ADCIRC hydrodynamic model executed for a period of one full year (2016), and thereafter the mean tidal range was extracted at different locations along the Odisha coast. Datasets pertaining to continental shelf slope, onshore topography, coastal geomorphology, and the rate of shoreline changes were estimated using Google Earth Imageries (2017), and the bathymetric information from National Oceanic and Atmospheric Administration (NOAA). The accuracy level of the Google Earth (GE) Imageries (2017) is much better than the previous versions. A recent study by Wang et al. (2017) for transportation applications highlights on the accuracy level of the

Table 1
Storm tide and inundation extent along major coastal locations of Odisha.

Place	Max. Surge (in meters)	Max. Inundation extent (in meters)	Volume (m^3)	Volume (in 10^6 L)
Baruva	2.1385	260	55601	55.601
Sonpur	2.7882	5000	1394100	1394.1
Gopalpur	2.2716	230	52246.8	52.2468
Ganjam	2.6140	1460	381644	381.644
Satapada	2.3543	2700	635661	635.661
Puri	3.3426	14500	4846770	4846.77
Konark	2.9065	19750	5740337.5	5740.3375
Jagatsingpur	3.5708	47000	16782760	16782.76
Paradeep	4.5138	62600	28256388	28256.388
Jambudeep	5.9057	51000	30119070	30119.07
Satavaya	4.1634	63300	26354322	26354.322
Dharma	5.7402	53000	30423060	30423.06
Chandipur	8.2015	20000	16403000	16403
Digha	7.3022	22000	16064840	16064.84
Mandarmani	6.8605	25000	17151250	17151.25

Table 2
Physical vulnerability parameters and their data sources.

S.No	Physical Parameters	Data Source
1	Storm Surge	Numerical Experiment: details in data section
2	Inundation Extent	Numerical Experiment: details in data section
3	Tidal Range	Numerical Experiment: details in data section
4	Rainfall	TRMM and IMD records
5	Slope of continental shelf	Estimated from Google Earth imageries and bathymetry from NOAA
6	Topographic slope	Estimated from Google Earth imageries and bathymetry from NOAA
7	Rate of shoreline changes	Estimated from Google Earth imageries
8	Coastal geomorphology	Obtained from Google Earth imageries
9	Mean wave height	Five years averaged (2012–2016) ECMWF (ERA-Interim) wave data along the coast
10	Relative sea level change	Rietbroek et al., 2016; Kusche et al., 2016; Unnikrishnan et al., 2006; Kumar et al., 2010

Google Earth Imageries (2017). Their study compared GE with other elevation data sources for USA, and for transportation applications it was found that the Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and GE roadway elevation error standard deviations are 1.32 m, 2.27 m, and 2.27 m respectively. The rainfall data (2010–2015) was obtained from Tropical Rainfall Measuring Mission (TRMM) and IMD (CRIS). The mean Significant Wave Height (SWH) was extracted from the European Centre for Medium Range Weather Forecast (ECMWF) Interim data covering the period 2012–2016. Information pertaining to relative sea level rise was collected from the studies by Unnikrishnan et al. (2006), Unnikrishnan and Shankar (2007), Kumar et al. (2010), Rietbroek et al. (2016), and Kusche et al. (2016).

2.3. Socio-economic and environmental vulnerability parameters

The demographic data available from the 2011 Census of India was used to calculate the social and economic vulnerability factors. Table 3 provides an overview on the aspects relevant to population density including vulnerable population, structural features, awareness system, transportation facilities, and the category of these exposures. The environmental or ecological vulnerability represents the risk of a location that has the ability to cope up and recover from the hazard. The data for environmental factors such as the Land-Use Land-Cover (LULC), mining, and industrial units, are obtained from the satellite data of Bhuvan maintained by the Indian Space Research Organization (ISRO). The LULC data (2011–2012) contains information relevant to the distribution of build-up, industrial areas, agricultural lands, forests, barren lands, and wetlands that have exposure as well resilience to the hazard. Finally the data on transportation facility includes the number of connecting roads and rail networks, available vehicles available in a locality (Table 3) obtained from the rail and road maps of India.

2.4. Methodology

During a tropical cyclone activity the physical parameters such as rainfall, SWH, tidal range, mean sea level rise, coastal and topographic slope, rate of shoreline change, coastal geomorphology, storm surge and inundation can lead to a multi-hazardous scenario in the affected locations. Whereas, the social parameters such as population density; rate of child, aged populations, and literacy; and lack of facility can multiply the vulnerability level of a given coastal location. The above mentioned datasets are analyzed using the ArcGIS toolbox to quantify the vulnerability that results from physical, social, and environmental drivers. The ArcGIS is a powerful visualization toolbox to represent features that can recognize the patterns and provide vital information to the users. The advantage in using this tool is its ability to handle and communicate voluminous diverse data into a single visualization platform. The representation of various datasets can be visualized in layers and then amalgamated to represent the combined effects of these environmental drivers along the coastal region. In addition specific color codes can be attributed to district and block-wise sections to assess the overall impact from multi-hazardous event in the affected regions. The Gornitz et al. (1997) formula expressed in index form was used in this study to assess the physical vulnerability of the coast from physical drivers and the social and environmental vulnerability index are estimated using Bahinipati (2014). The combination of PVI, SVI, and EVI in turn provides the resultant CVI along various coastal districts of Odisha state.

The mathematical formula to estimate physical PVI was reported by Gornitz et al. (1997) is being widely used. The first step to calculate PVI deals with identification of key parameters or the drivers that influences the risk associated in a coastal region. Generally the PVI formulation includes about 6–7 variables, and the U.S. Geological Survey (USGS) considered the variables such as geomorphology, rate of change in shoreline, coastal slope, relative sea level rate, mean significant wave height, and mean tidal range. The number of parameters or drivers may change based on the local dynamics of the study region. The second step deals with quantification of the identified key variables and allocating appropriate quantitative scores in a chronological scale (for example, scale of

Table 3
Data sources for social vulnerability.

S.No.	Data	Data Type	Category	Source of data
1	Population Density	Number of persons per block/district	Exposure	Census India 2011
2	Vulnerable population	Old, children, sick and disabled population	Susceptibility	
3	Structural features	Distribution of cyclone/flood proof buildings, rescue homes, concrete houses	Resilience	
		Other than concrete house	Exposure	
4	Awareness system	Education rate, TV and Mobile phones, and vehicles per house	Resilience	
5	Land-Use & Land-Cover (LULC)	Distribution of build-up, industrial areas, agriculture lands	Exposure	Bhuvan, ISRO
		Forests, barren lands	Resilience	
		Wetlands	Resilience	
6	Transportation Facilities	Number of connecting roads and rail networks, and available vehicles in the locality	Resilience	Rail and Road Maps of India

1–5), wherein the lowest score of 1 indicates low contribution to coastal vulnerability of a specific key variable for sub-areas in the study domain, while a score of 5 indicates the highest contribution. The third step involves aggregation of various key variables into a single index using a mathematical formula. The formulation is given by Gornitz et al. (1997):

$$PVI = \sqrt{\text{variable}(m_1) \times \text{variable}(m_2) \times .... \times \text{variable}(m_{n-1}) \times \text{variable}(m_n)/n},$$

where $m_1, m_2, ..., m_n$ are the variables and n is the total number of variables. The physical variables used in this study is ranked in Table 4.

According to Bahinipati (2014), the components are normalized using basic normalization technique and the aggregate vulnerability by this study is estimated by, $CVI = \sum_{i=1}^{n} X_i/n$, where X_i is the ith component of vulnerability, n is the total number of components used in the study. If the component (X_i) has reverse effect on vulnerability then it is subtracted from 1 to get a uniform scaling. The variables have reverse effect on vulnerability have been plotted in flipped color scale.

3. Results and discussion

There are many regions exposed to several types of natural hazards having their own spatial characteristics. It is evident that the impacts of disasters have also increased in the past few decades, and the possible reason attributes to increased frequency of extreme weather events linked with climate change and increased exposure to vulnerable population. Therefore, disaster risk management dealing with aspects on hazard assessment, key elements in risk mapping, vulnerability and risk assessment have important socio-economic implications. The Intergovernmental Panel on Climate Change (IPCC, 2007) reported on a trend since the mid-1970s on longer duration and storms with higher intensity that had a strong correlation with rise in the tropical ocean sea surface temperature. At present there is a consensus amongst the global scientific community for greater disaster preparedness in countries that are vulnerable to storm surges resulting from tropical cyclones. Gao et al. (2014) reported on risk assessment of tropical storm surge for the coastal regions of China. They performed a detailed analysis and developed a vulnerability assessment index based on socio-economic, land use, ecological environment, and resilience data. Hazard and risk assessment can be carried out at different scales ranging from global to a regional scale. A proper understanding on the characteristics of risk associated with tropical cyclones for the coastal regions of India especially along the East coast of India is of great interest. A comprehensive study considering vulnerability associated with various environmental drivers is very essential for risk assessment of the coastal region. A comprehensive picture on vulnerability indices based on factors like socio-economic, land use land cover, ecological environment, and resilience is very essential to bring out a clear picture on the vulnerability levels. The subsequent provides an overview on the global and regional scale implications of this study with emphasis on multi-hazard assessment of coastal vulnerability from tropical cyclones.

3.1. Vulnerability study based on inundation volume

Based on research findings it is evident that there would be substantial increase in the number of most severe tropical cyclones globally (Webster et al., 2005; Elsner et al., 2008). Knutson et al. (2010) advocates that the global averaged intensity of tropical cyclones continue to shift towards stronger storms and the expected increase would be from 2% to 11% in the global ocean basins. The inundation volume is a better representation in context to flooding associated with tropical cyclones. It is a combination of storm tide and flooding providing a detailed overview on the spatial extent of inland inundation. Prior studies conducted for the Indian coast in context to coastal vulnerability have considered parameters such as storm tide and inundation independently. However, the vulnerability aspects considering their combined effects have not been reported. The authors are of the opinion that considering inundation volume is a better indicator as compared to the traditional methods used so far. It is seen from Table 1 that there is no linear relation between the quantities storm tide and inland extent of onshore inundation. This is expected as the local geomorphic features, bottom friction, and onshore topography can influence the

Table 4
Ranking of physical coastal vulnerability index.

Variable	Very low 1	Low 2	Moderate 3	High 4	Very high 5
Coastal Slope (%)	>0.2	0.2–0.07	0.07–0.04	0.04–0.025	<0.025
Relative Sea level change (mm/yr)	<1	1 to 2	2 to 3	3 to 4	>4
Shoreline change (m/yr)	>6.0 Accretion	3.0 to 6.0	−3.0 to 3.0 Stable	−3.1 to −6.0	<−6.0 Erosion
Mean tidal range (m)	<1	1.0 to 2	2.0 to 4.0	4 to 6.0	>6
Mean Sig. wave height (m)	<0.5	0.5 to 0.8	0.8 to 1.1	1.1 to 1.4	>1.4
Geomorphology	Rocky, Cliffed coast, Fjords	Medium cliffs, Indented coast	Low cliffs, Glacial drift, Alluvial plains	Cobble beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangrove, Coral reefs
Rainfall (mm)	<100	100 to 200	200 to 300	>300	>300 and thunderstorm
Storm Surge (m)	<2	2 to 3.5	3.5 to 5	5 to 7.5	>7.5
Inundation (length × width)	<500 m × 500 m	1 km × 1 km	5 km × 5 km	10 km × 10 km	>10 km × 10 km
Cyclone Intensity (knot)	110	120	130	140	150

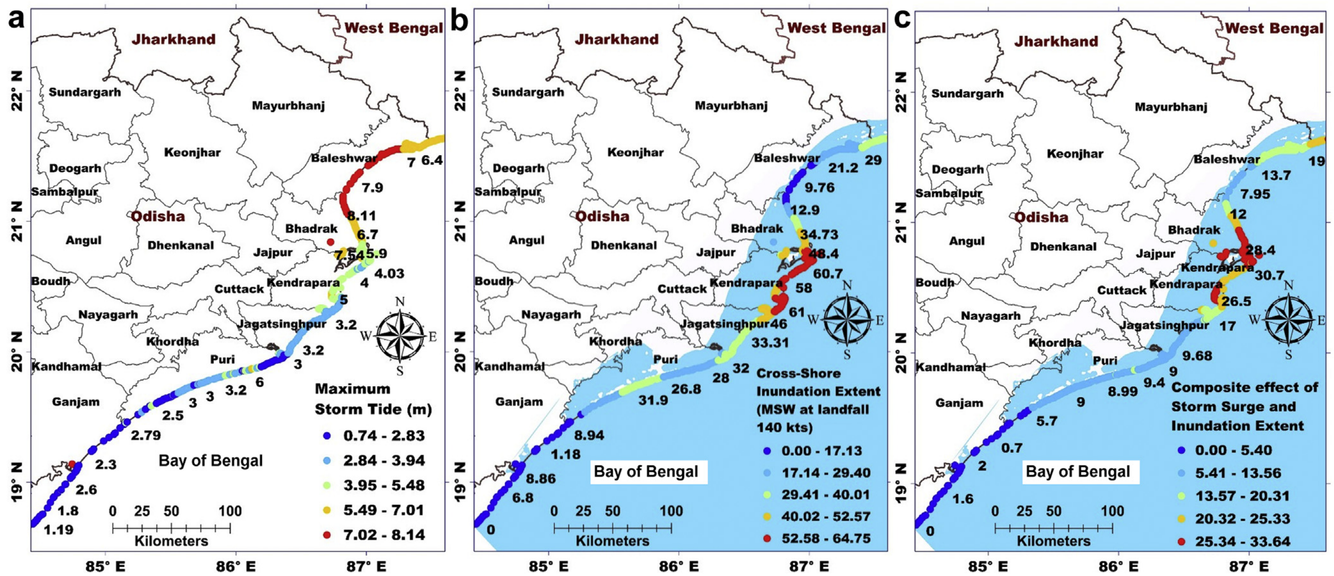

Fig. 1. (a) Maximum Storm tide, (b) Cross-shore inundation extent, and (c) combined effect of storm tide and cross shore inundation.

variability in the spatial extent of onshore inundation characteristics. In other words a smaller elevation of water level near the coast can inundate larger areas of a low-lying coastal belt. As there is no specific relation found between storm tide and the extent of inland inundation, the authors feel it would be worthwhile to evaluate the extent of inundation in terms of inundation volume.

Fig. 1 shows the spatial variability of storm tide, cross-shore inundation extent, and the inundation volume along the Odisha coast. The study signifies that the overall storm tide range varied between 0.7 m and 8.0 m from south to north respectively for the 480 km long coastline. These values are important in context to regional scale (confined to the Odisha coast); however the magnitude of these values can be much higher in a global sense. For example, the tidal range is much higher in the head Bay of Bengal region bordering the West Bengal State (Rose and Bhaskaran, 2017) as compared to the neighboring Odisha State. The range can be in excess of 5.0 m at some locations (Rose and Bhaskaran, 2016) in the head Bay region. In addition, the presence of deltaic fan with numerous riverine inputs, tidal creeks, shallow and wide continental shelf in the shelf region off West Bengal can lead to surge amplification. A recent study by Gayathri et al. (2016) considered the case of hypothetical storm surge and coastal inundation associated with a severe cyclone AILA that had landfall in the West Bengal coast. Their study reported a peak storm surge of 4 m in the

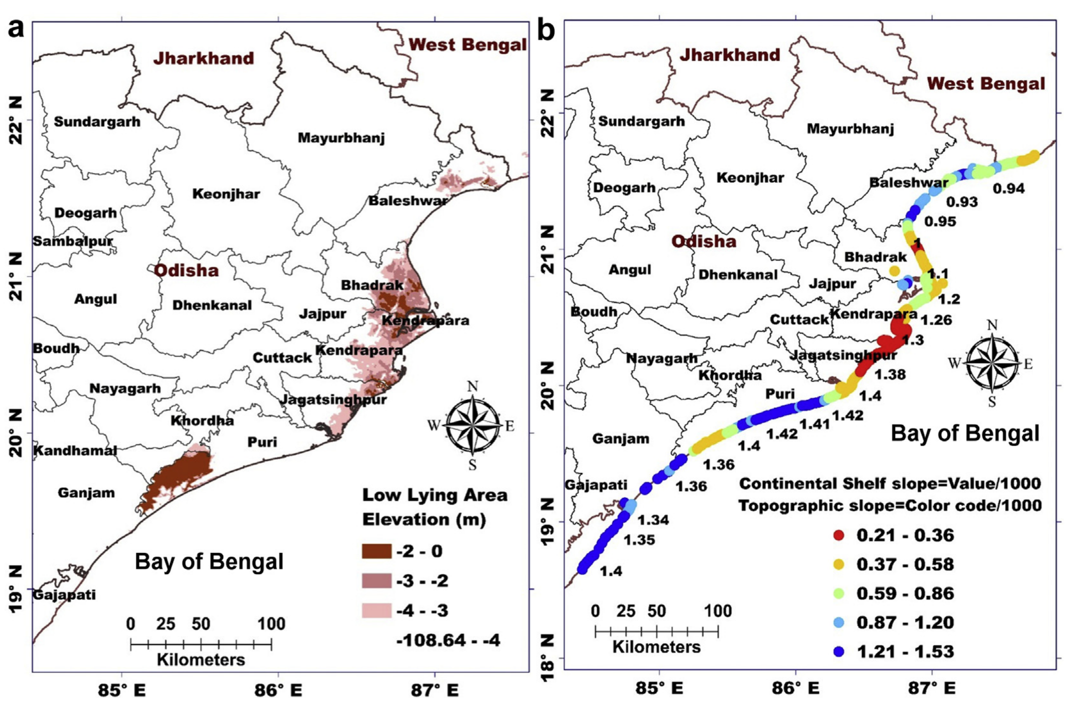

Fig. 2. (a) Low-lying areas, and (b) topographic slope and continental shelf slope along coastal Odisha.

Sundarban region with an average inland penetration distance of 350 m, and a maximum of about 600 m along various coastal locations in West Bengal and Bangladesh. During high tidal conditions the occurrence of storm surge over this region can result in storm tide much higher as compared to Odisha coast. Therefore, in a global perspective introducing the concept of inundation volume is very much relevant in context to coastal vulnerability and risk associated with tropical cyclones.

For the Odisha State the districts such as Bhadrak and Balasore located in the northern part are the highest vulnerable regions with storm tide exceeding 7.0 m (Fig. 1a). The Ganjam district has the lowest vulnerability, whereas the districts located in the central region such as Puri, Jagatsinghpur, and parts of Kendrapara show that storm tide varied between 2.8 and 4.0 m. The cross-shore inundation (Fig. 1b) clearly reveals that Jagatsinghpur, Kendrapara, and Bhadrak districts are highly susceptible to inundation associated with storm surge during cyclone landfall. For a maximum sustained wind speed of 140 knots (during landfall), the maximum cross-shore extent of inundation in Kendrapara district is about 65 km. The combined effect of storm tide and inundation (shown in Fig. 1c) clearly indicate that Kendrapara and Bhadrak districts are relatively the highest vulnerable areas along the Odisha coast.

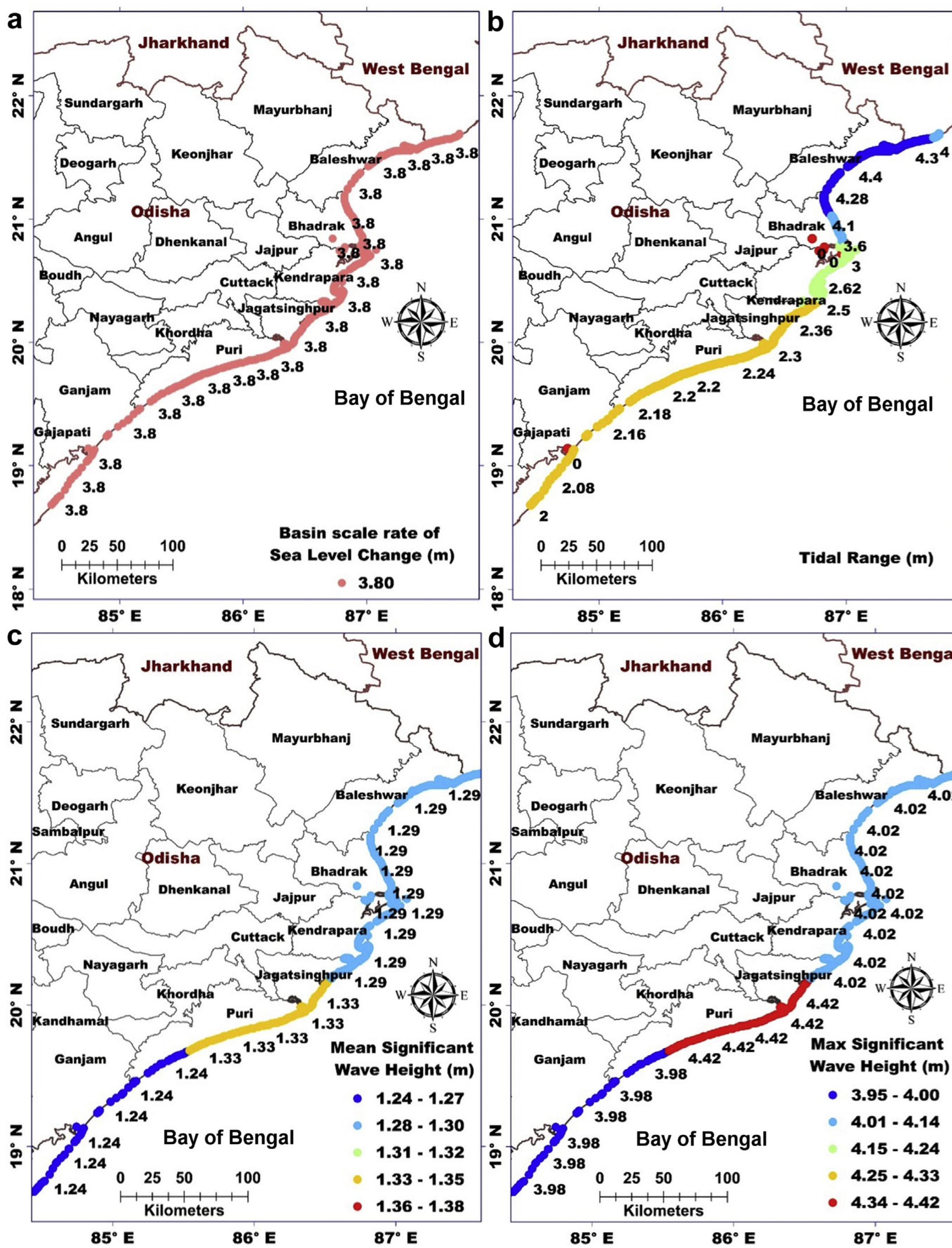

Fig. 3. (a) Rate of sea level change, (b) tidal range, (c) mean significant wave height, and (d) maximum significant wave height along Odisha coast.

3.2. Assessment of physical vulnerability

The various physical parameters that contribute to physical vulnerability are shown in Table 2. The contribution from each independent parameter listed in this table has an important role in the overall determination of PVI. The low-lying areas along the Odisha coast are shown in a map (Fig. 2a) for regions having elevation less than 4 m. In a global perspective, the nearshore regions of neighboring West Bengal have elevations much lower than this value leading to a much higher risk and vulnerability levels. Most of the coastal belt in the southern part of the Gangetic delta is lower than 2 m above mean sea level. Nayak and Bhaskaran (2014) have conducted assessment of coastal vulnerability due to extreme waves based on historical tropical cyclones for a stretch of 250 km in the Tamil Nadu state with Kalpakkam as the focal point. Their study reveals that regions north of Kalpakkam between Pulicat to Chennai are at higher risk, whereas the vulnerability in other regions of Tamil Nadu varied between low to moderate. However, the vulnerability and risk level in Tamil Nadu as compared to Odisha State is much lower.

In context to Odisha coast, the coastal belts of Jagatsinghpur, Kendrapara, Bhadrak, and Balasore are the low-lying areas that are not only susceptible to coastal inundation, but also has an additional risk associated with river flooding from major riverine systems. The ADCIRC model used in this study also compute the storm surge and inundation surrounding the Chilika Lake region. However, in a historical perspective it is evident that this region has no threat in context to coastal flooding. Hence, the surrounding areas of Chilika Lake in the Puri district is not accounted in this study as a major threat from coastal flooding. Fig. 2b depicts the slopes of continental shelf and onshore topography. Regions having slope values that are low and very low can escalate the storm surge height near coast, and trigger the onshore propagation of storm surge that can result in the inundation of low-lying areas. It is also evident that coastal locations in the Kendrapara and Jagatsinghpur districts in central Odisha have lower slopes having potential risk and therefore vulnerable to storm surge and inundation characteristics. Relatively the slopes are higher in the southern part of Odisha state. Fig. 3 shows the map for the rate of sea level change, tidal range, mean and maximum SWH. The rate of sea level change for the Bay of Bengal basin is reported as 3.8 ± 3.2 mm/year based on the analysis from altimeter survey (Rietbroek et al., 2016). It indicates that the coastal belt bordering the Bay of Bengal is at a high risk. The rate of sea level rise over this region is relatively higher as compared to the other global ocean basins. For the Odisha coast a constant value of 3.8 mm/year is considered in this study despite of local sea level changes. Fig. 3b shows the tidal range (in meters) along the coastline computed using the ADCIRC model. It varied between 2 m and 4.5 m having a direct dependence on the slope and width of the continental shelf. The mean and maximum SWH distributions are shown in Fig. 3c and d respectively. Along most of the coastal areas in south Odisha the mean and maximum SWH are less than 1.3 m and 4.0 m. It is relatively higher for Puri and Jagatsinghpur districts, whereas the other districts in north Odisha have mean and maximum SWH about 1.3 m and 4.0 m respectively. Over the northern regions especially during extreme weather events like tropical cyclones the maximum significant wave heights can rise up to 9 m.

Fig. 4a provides an overview on the geomorphic features related to the riverine waterways in the Odisha state. As seen from this figure the districts of Jagatsinghpur and Kendrapara have a high network of riverine tributaries, and therefore it is a high risk prone area in context to riverine flooding. The situation can worsen if tropical cyclone have landfall in one of these districts as the storm surge can penetrate into these riverine systems and can inundate the low-lying flood plain areas. The percentage shoreline changes that include both erosion and accretion are shown in Fig. 4b. This information was obtained from the National Assessment of Shoreline Change report (Ramesh et al., 2011). In a relative sense, the Bhadrak and Ganjam districts exhibits the highest and lowest percentage respectively. Overall the changes are relatively higher in the north Odisha coast as compared to the south. Shoreline changes have direct implications on the local hydrodynamic conditions, sediment transport mechanism that can in turn affect the storm surge and inundation characteristics during tropical cyclone activity. Fig. 4c shows the average rainfall (in mm) during the period from 2010 to 2015. It is evident from the data that central districts such as Jagatsinghpur, Kendrapara and Balasore receive the highest average rainfall as compared to the other districts. The physical vulnerability in terms of low-lying areas (Fig. 2a) and waterway

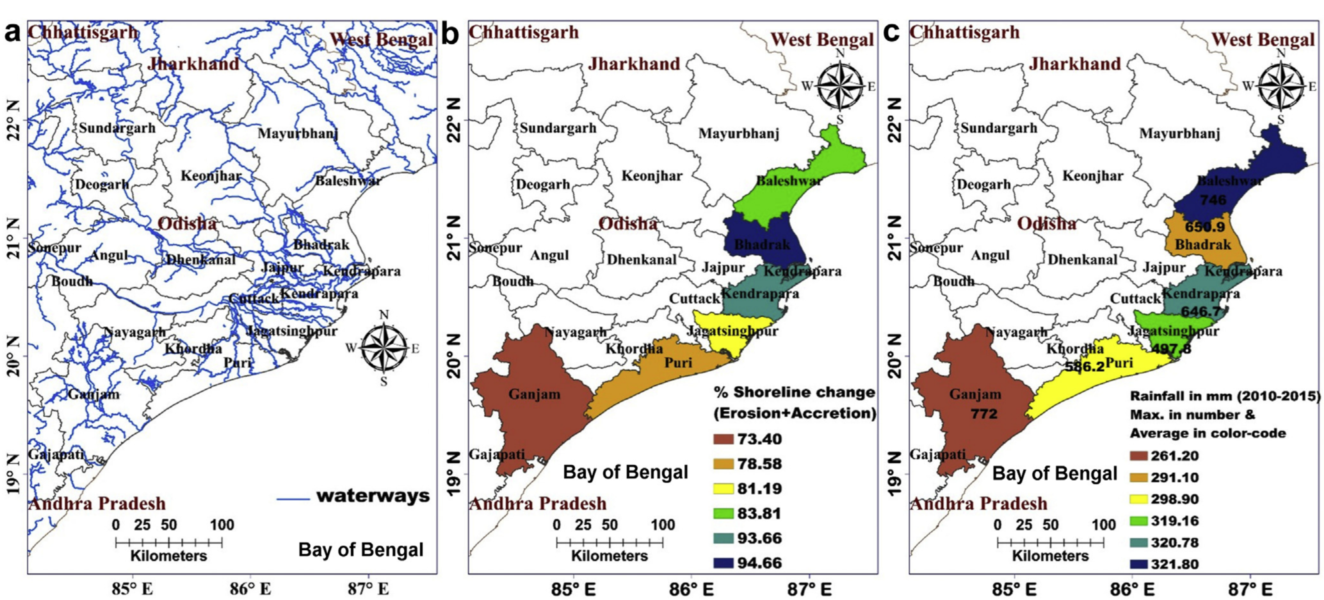

Fig. 4. (a) Coastal geomorphology, (b) Percentage shoreline change, and (c) Average rainfall during 2010–2015.

Table 5
District wise PVI, SVI, EVI, and CVI.

Districts	PVI	SVI	EVI	CVI
Ganjam	0.01	0.67	0.21	0.30
Puri	0.02	0.88	0.58	0.49
Jagatsinghpur	0.53	0.68	1.00	0.74
Kendrapada	1.00	0.46	0.88	0.78
Bhadrak	0.29	0.65	1.00	0.66
Balasore	0.26	1.00	0.67	0.64

networks (Fig. 4a), regions in the central Odisha with higher average rainfall have additional risk factor associated with inland flooding as compared to the other districts. The Ganjam location in south experiences the lowest average rainfall. In a changing climate scenario there are uncertainties associated with the patterns in rainfall distribution, and it warrants a separate detailed study. All the above mentioned environmental drivers (shown in Figs. 1–4) are used in the present study. Finally the Gornitz et al. (1997) formula was used to obtain the combined PVI. Table 5 shows the relative PVI considering all the above mentioned environmental drivers for selected districts of the Odisha state.

3.3. Assessment of socio-economic vulnerability

Several prior studies have reported on PVI for different coastal states of India. However, it is constrained to have its potential unless its impact on ecosystem is thoroughly investigated. In this context parameters pertaining to social, economic, and environmental vulnerability find its importance, and the present study deals with these aspects to provide information on the multi-hazard risk assessment. The response of social, economic, and environmental units of the ecosystem towards physical vulnerability depends on the resilience capacity and adaptive nature of the affected ecosystem. In addition, the resilience and adaptive nature of a coastal ecosystem in response to hazard are highly dynamic in temporal and spatial scales. Hence, to study the vulnerable ecosystem and its vulnerability is a relative concept. Other issues

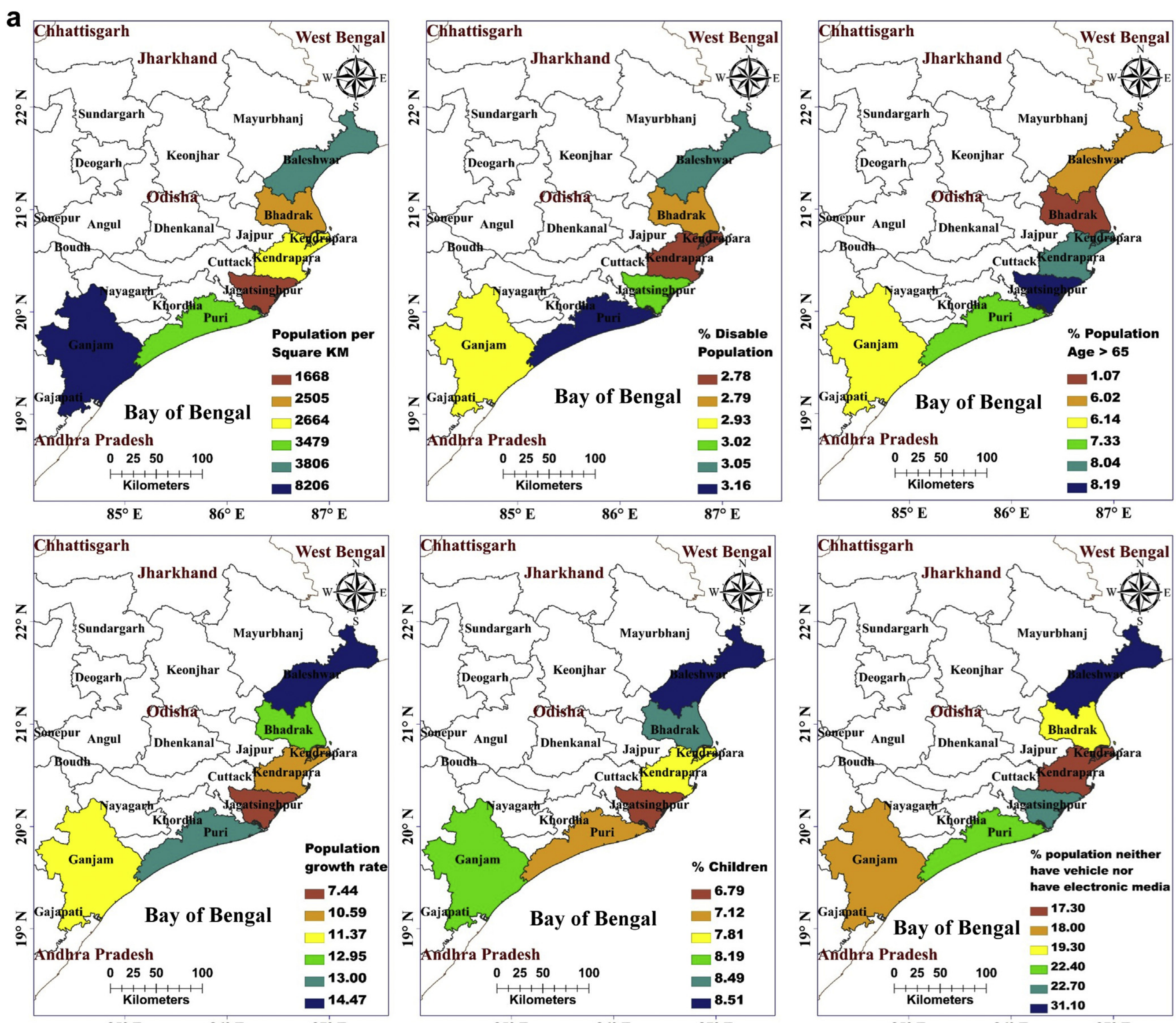

Fig. 5. (a) Social vulnerability parameters categorized under risk. (b) Social vulnerability parameters categorized under resilience.

such as resolution and quality of the archived data can also affect reliable estimates of SVI and EVI. In the present study no weightage is assigned for the estimation of SVI. Fig. 5a presents various aspects on the data of human population that can be directly under risk during a multi-hazard scenario (Census Digital Library, India). The population density (per square km of area) and other vulnerable population such as the disabled population, children, and senior citizens (shown in various panels of Fig. 5a) are highly exposed to risk when higher in value. A recent study by Mazumdar and Paul (2016) investigated the socio-economic and infrastructural vulnerability indices associated with cyclones for the eastern coastal states of India. Their study considered 12 coastal districts for SVI assessment such as West Medinipur in West Bengal State; (Baleshwar, Bhadrak, Kendrapara, Jagatsinghpur, Cuttack, Jajpur, Puri, and Ganjam in Odisha State); (Chittoor in Andhra Pradesh); (Thiruvarur and Tirunelveli in Tamil Nadu State). A total of 7 coastal districts covering East Medinipur, Kolkata, North 24 Parganas, Hooghly and Howrah in West Bengal State; Prakasam in Andhra Pradesh, and Yanam in Puducherry were considered for the Infrastructural Vulnerability (InVI) assessment. In addition, a total of 4 coastal districts covering South 24 Parganas (West Bengal State), Gajapati (Odisha State), Srikakulam and Vizianagaram (Andhra

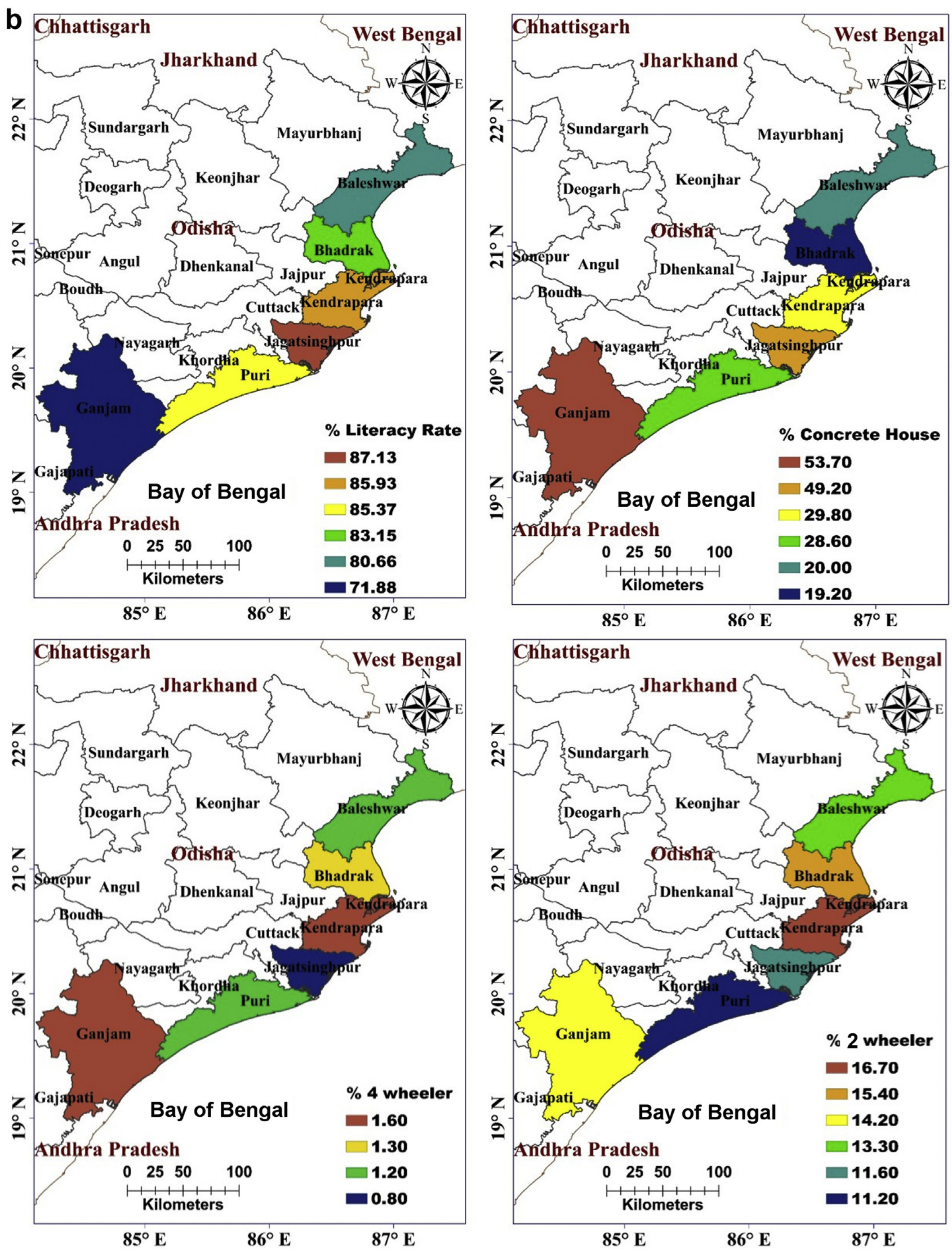

Fig. 5. (*continued*).

Pradesh) were used to investigate the combined effect of PVI and InVI. Mazumdar and Paul (2016) indicates that spatial mapping of SVI and InVI showed a strong regional variation in the socio-economic and infrastructural vulnerability across various districts bordering the East Coast of India. Also vast majority of districts in Odisha State showed a high level of social vulnerability followed by neighboring states of Andhra Pradesh, West Bengal, and Tamil Nadu. The infrastructural vulnerability is substantially higher in the eastern districts of West Bengal as compared to the other states. Their study (Mazumdar and Paul, 2016) also indicate there are cluster of highly vulnerable districts in south coastal Odisha and northern Andhra Pradesh.

In context to Odisha State, the highest population density is at Ganjam in the south followed by Balasore district in the north (that has a high risk in context to physical vulnerability). The population densities in the other districts are moderate. The maximum percentage of disabled population is about 3% and the highest is seen for the Puri district. The spread is more or less uniform over all the coastal districts. The Jagatsinghpur district has the highest percentage of senior citizens followed by Kendrapara with about 8%. Similarly the Balasore district in the north has the highest population growth rate and percentage of children and population having neither vehicle nor the electronic media. The decadal growth rate in population is an indicator of risk in the future. Also the population having no electronic gadgets for information during a calamity as well limited access to vehicles for evacuation is considered in the risk category.

Fig. 5b shows the parameters such as rate of literacy, percentage distribution of concrete houses, four- and two-wheelers listed in the resilience category. These dataset finds importance for preparedness and evacuation planning operations during tropical cyclone activity. The layers shown in Fig. 5a and b are stacked into one layer, and the tabular form of composite SVI for the coastal districts of Odisha are shown in Table 5. The study signifies that districts of Balasore followed by Puri are the most vulnerable in terms of tropical cyclones considering the social vulnerability parameters. The Land-Use and Land-Cover (LULC) map for various coastal districts of Odisha are obtained from the satellite imageries of Bhuvan (ISRO). A more detailed overview on this aspect individually categorized as build-up, agriculture, barren lands,

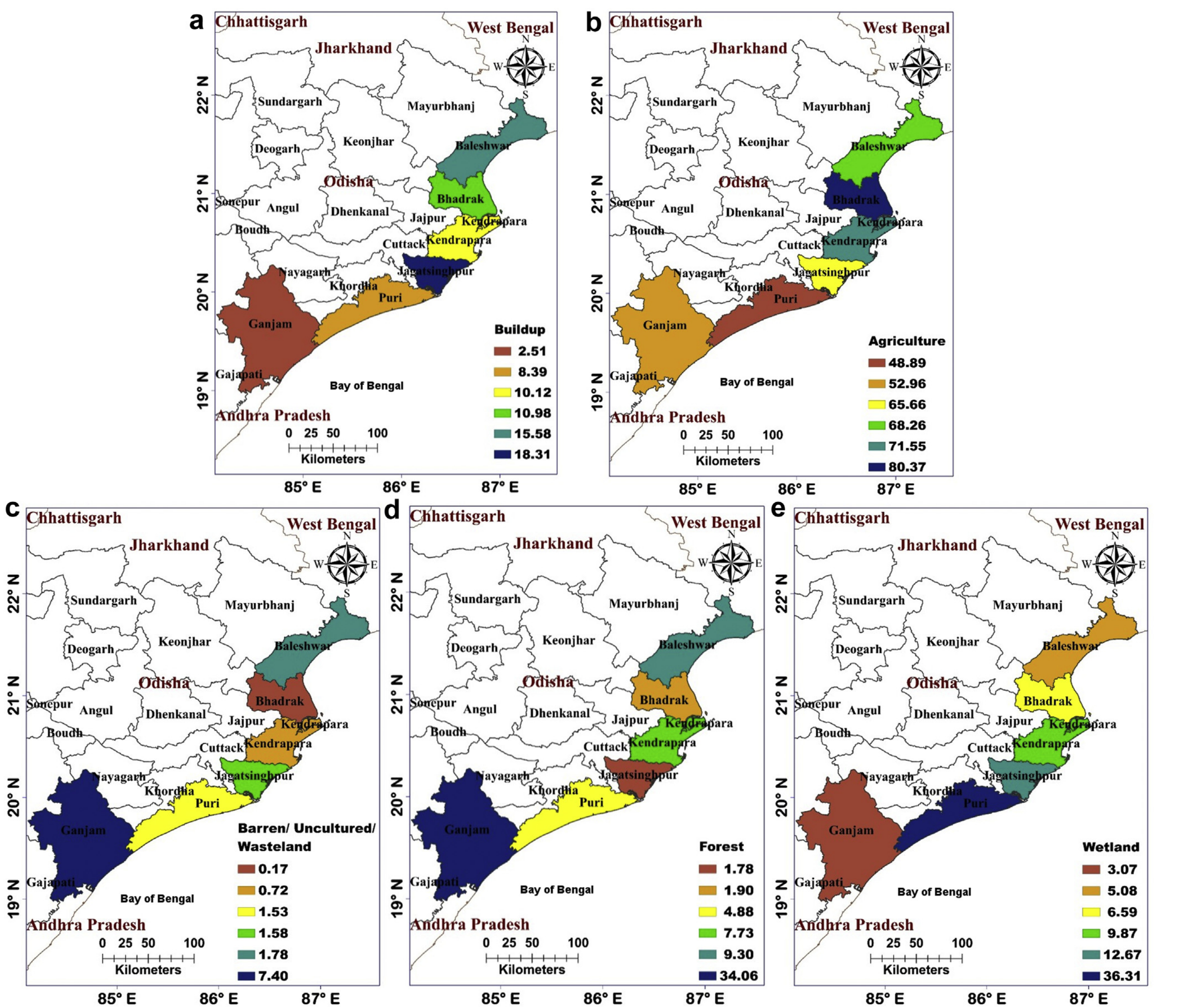

Fig. 6. Dataset of (a) Build-up, (b) Agriculture, (c) Barren and Wasteland, (d) Forest, and (e) Wetlands along Odisha state.

wastelands, forest, and wetlands are shown in Fig. 6. As seen, the Jagatsinghpur district is at a high risk based on the percentage of build-up that includes rural-urban build-up and mining area (Fig. 6a) followed by Balasore and Bhadrak. Larger areas of agricultural land cover over Bhadrak, Kendrapara, and Balasore districts (Fig. 6b) is exposed to risk from coastal flooding, river flooding and rainfall during tropical cyclone landfall. On the other hand forest, barren lands, wastelands, and wetlands acts as a natural barrier to wind gust, storm surge, and inundation during a cyclone. With rapid urbanization converting this natural habitat to build-up exposes these areas to risk from natural hazards. An overall analysis of these environmental drivers (shown in Fig. 6) signifies that Ganjam district is the least exposed, whereas other coastal districts such as Bhadrak, Jagatsinghpur, and Kendrapara are at a higher risk (Table 5). The composite maps of physical, social, economic, and environmental vulnerability are normalized and stacked using ArcGIS to provide an integrated picture of CVI for the entire Odisha coast (Table 5). The study signifies that Kendrapara district has the highest value of CVI. It is followed by Jagatsinghpur, Bhadrak, Balasore in the central and north Odisha that are moderately vulnerable, and Ganjam district in the south has the lowest CVI based on the combined effects of PVI, SVI, and EVI.

4. Summary and conclusion

The Bay of Bengal in the North Indian Ocean basin is very active in the formation of tropical cyclones as compared to the Arabian Sea. On an average about 4–6 cyclones develop over this region that make landfall along the East coast of India, Bangladesh and Myanmar. Cyclones that form over this region exhibit a double peak, one during the pre-monsoon period and other during the post-monsoon season. As compared to storms in the global oceans, the frequency (~4–6 per year) in Bay of Bengal is much lower as compared to the western Pacific Ocean (annual average of about 25 per year). However, considering other factors such causalities, loss of life, damage to infrastructure, etc. associated with tropical cyclone strikes the countries surrounding the Indian Ocean rim is at a high risk. Especially the Odisha State experiences the highest number of cyclone strike compared to West Bengal, Andhra Pradesh, and Tamil Nadu. Keeping this in view, the present study performs a comprehensive analysis on the determination of composite CVI based on physical, social, economic, and environmental vulnerability for the coastal districts of Odisha state due to extreme weather events such as tropical cyclones. In terms of exposure to cyclone strikes, the vulnerability level of Odisha is much higher as compared to the other states West Bengal, Andhra Pradesh, and Tamil Nadu and hence the importance of this study. As per the 2011 Census from Government of India, about 33% of the total population in Odisha state resides along the coastal districts. Major cities and tourist attractions are situated along the coastal belt. The study attempts to construct pre-computed scenarios of storm surge and inundation for the entire coastal belt of Odisha including the scenario expected in a changing climate. The authors believe that a comprehensive database used in this study generated using multiple synthetic tracks are attempted for the first time in context to the Indian coast. This information coupled with physical, social, and environmental vulnerability aspects resulted in the generation of a composite CVI that is very much useful for proper planning and preparedness measures. The ADCIRC model was used to generate multiple scenarios of storm surge and inundation at various locations along the 480 km coastal stretch of Odisha. One of the highlights resulting from this study is coastal vulnerability expressed in terms of inundation volume in addition to other environmental drivers such as mean tidal range, rainfall, significant wave height, sea level change, and coastal geomorphology. A ten parameter model was used to estimate PVI, and in addition the study also deals with aspects on social, economic, and environmental vulnerability using the ArcGIS tool. By considering all the above mentioned factors the study reveals that Kendrapara and Jagatsinghpur districts located in central Odisha are the highest vulnerable regions, whereas the northern portions are moderately vulnerable.

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